Underground Muon Physics with the MACRO experiment

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Underground muon events detected by the MACRO experiment at Gran Sasso have been studied for different purposes. The studies include the vertical muon intensity measurement, multiplicity distribution, lateral and angular muon distribution and searches for substructures inside muon bundles. These analyses have contributed to bring new insights in cosmic ray physics, in particular in the framework of primary cosmic ray composition studies. Moreover, this activity allows the testing and tuning of Monte Carlo simulations, in particular for aspects associated with models of hadronic interactions and muon propagation through the rock.

1. INTRODUCTION

Muons detected deep underground are a useful tool for different physics and astrophysics items. These muons are the decay product of mesons originating in the very first hadronic interactions in the atmosphere or in secondary interactions during the shower development. Therefore, their study can provide many informations about primary cosmic rays (CR) composition and/or high energy hadronic interactions. Muons arriving in the underground Gran Sasso Laboratory have crossed at least $h \geq 3100$ hg/cm^2 of standard rock, corresponding to a muon energy cut $E_\mu \geq 1.3$ TeV at the surface. This means that the primary CR energies range from some TeV/nucleon up to the maximum energies well beyond the "knee".

The MACRO experiment has collected a large amount of muon data in the last decade, at a rate of $\sim 6.6 \times 10^6$ muon events/live year, and the $\sim$ 6% of these are multiple muon events. Many underground observables have been studied. The multiplicity distribution, i.e. the rate of muon events as a function of their multiplicity, is a quantity strongly dependent on the primary composition model. A detailed analysis on primary composition has been performed by the MACRO collaboration [1,2]: one of the result is that data prefers a composition model with an average mass slightly increasing with energy above the knee[2].

Nevertheless, in the context of composition studies the knowledge of the hadronic interaction model is crucial. The main contribution to the systematic uncertainties in these analyses are due to the interaction models adopted and it is important to find out new observables to test the reliability of these models implemented in the Monte Carlo simulations. Moreover, is intrinsically important to test interaction models in kinematical regions not yet explored at accelerators or colliders. For instance, about 5% of MACRO muon data comes from pp interactions with $\sqrt{s} > 2$ TeV, while about 30% of the muons observed are the decay products of mesons produced with a (pseudo)rapidity $\eta_{cm} > 5$. The situation is more evident if we consider that part of primary interactions in the atmosphere are nucleus-nucleus interactions, and very few data for energy $E_{lab} \gtrsim$ 150 A GeV are available. In the following, we will focus on the decoherence analysis and on cluster analysis, two different tools able to extract informations on the interaction model adopted in the simulation codes.

2. THE MACRO DETECTOR

The MACRO detector [3] is a large area apparatus located in hall B of the Gran Sasso Laboratory at an average depth of 3800 hg/cm^2 of standard rock ($E_\mu \geq$ 1.3 TeV). It has a mod-

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[2]for a more detailed discussion on composition studies see the contribution of E. Scapparone in these proceedings

ular structure, organized in six almost identical "supermodules" covering an horizontal surface area of $\sim$ 1000 m^2. The apparatus is equipped with three different and independent sub-detectors: streamer tube chambers for particle tracking, scintillator counters for timing and energy loss reconstruction and nuclear track-etch detectors optimized for the search of magnetic monopoles. The wire view of the streamer tube system is complemented with a second view, disposed at 26.5° with respect to the wire view, realized with aluminium pick-up strips. The spatial resolutions are σ_W=1.1 cm and σ_S=1.6 cm for the wire and strip view respectively. This arrangement allows the 3-D track reconstruction with an intrinsic pointing resolution of 0.2°.

3. SIMULATION TOOLS

The full simulation chain used to interpret MACRO data is composed of an event generator modelling high energy hadronic interactions, included in a shower propagation code which follows particles above threshold up to a given atmospheric depth. A muon transport code propagate muons inside the mountain overburden the apparatus and a detector simulator produces an output in the same format of real data.

• **Event generator**

Most of the analyses of MACRO data have been carried on using the original HEMAS interaction model [4], based on the parametrizations of minimum bias events collected at the $Sp\overline{p}S$ collider at CERN [5]. According to these results, the charged multiplicity is sampled from a negative binomial distribution and the transverse momentum contains a power law component. The model includes nuclear target effects and extrapolations to higher energies are performed in the context of $\log(s)$ physics.

The interaction model in Ref. [6] (called "NIM85") has been tested in a parametrized form with MACRO muon data [8,19]. This model neglects some important experimental results: for instance, the charged multiplicity is sampled from a Poisson distribution and the transverse momentum distribution contains only a pure exponential functional form.

Presently new interaction models are under study: DPMJET [10], QGSJET [11], SIBYLL [12] and HDPM, the original interaction model of the shower simulation code CORSIKA [13]. These are phenomenological models where the interactions are treated at parton level, with the exception of the HDPM generator, which is based on the DPM model but it is built according to parametrized results. They have the common feature to refer to the Regge-Gribov theories for the modelling of the soft part of the interactions, where perturbative QCD cannot be applied. Nevertheless, the transverse component of the interactions is not constrained by the theory and is introduced "by hand", according to some experimental results such as the seagull effect [15] or the Cronin effect [14] in nuclear interactions. In this context, it is useful the comparison of the model one to each other to estimate the systematic uncertainty associated to the unknown transverse structure of the interactions.

• **Cascade code**

Two different shower propagation codes have been used in the analyses: HEMAS[3] [4,7] and CORSIKA [13]. HEMAS is conceived as a fast tool to compute the hadronic, electromagnetic and muon component of air showers. It has been extensively used in the MACRO collaboration and has revised many improvements since its first release. It introduces some approximations in the shower development, so that the model can be used to follow only particles with a minimum energy in atmosphere $E > 500$ GeV. The electromagnetic size is computed by means a semi-analytical method. It can be used interfaced with the DPMJET and HEMAS interaction models.

Recently, the CORSIKA [13] Monte Carlo code, generally used in surface EAS-arrays, has been interfaced with the muon transport code to propagate muons up to the Gran Sasso depth. This code has been used only in the analysis of high multiplicity events.

[3]the name HEMAS refers both to the hadronic interaction model and to the cascade code

• **Muon transport code**
The muon propagation in the rock has been realized using the PROPMU package [16], which represents an improvement with respect to the propagation model included in the original HEMAS version. It takes into account muon energy loss due to multiple Coulomb scattering and to discrete processes, such as bremsstrahlung, pair production processes and photonuclear interactions.

• **Detector simulator**
The response of the apparatus is simulated by means a GEANT [17] based code, called GMACRO. It reproduces all relevant physical processes in the detector and produces an output in the same format of real data, so as to process data using the same offline chain of real data.

4. ANALYSIS RESULTS

4.1. Decoherence Function

The *decoherence function*, defined as the distribution of the muon pair separation in multiple muon events, is mainly connected with the muon lateral distribution with respect to the shower axis and is very sensitive to the transverse structure of the hadronic interaction models. The decoherence distribution is instead weakly dependent on the primary composition model, as far as the shape of the distribution is concerned. Therefore, the study of this function allows to some extent the disentangle between the two effects. MACRO has studied the decoherence function up to the maximum distance allowed by the apparatus [9] (~ 70 m). The unfolded decoherence function (the distribution corrected for the detector effects) is shown in Fig.1, where it is compared with the predictions of the HEMAS Monte Carlo.

A further check on the reliability of the simulation code has been performed in different rock/zenith windows, constraining some component of the shower development with respect to others [9]. Again, the comparison shows a good agreement between data and Monte Carlo.

Finally, the study of the decoherence function in the very low distance region has shown that the QED process $\mu^{\pm} + N \rightarrow \mu^{\pm} + N + \mu^{+} + \mu^{-}$ at small distances must be taken into account if we want to reproduce the experimental data [21]. This is shown in Fig.2, where the low distance region of the decoherence function is shown before and after the correction. The contribution of this process is negligible compared to the $e^{+}e^{-}$ pair production process in the GeV range, but it becomes progressively more important in the TeV region [18].

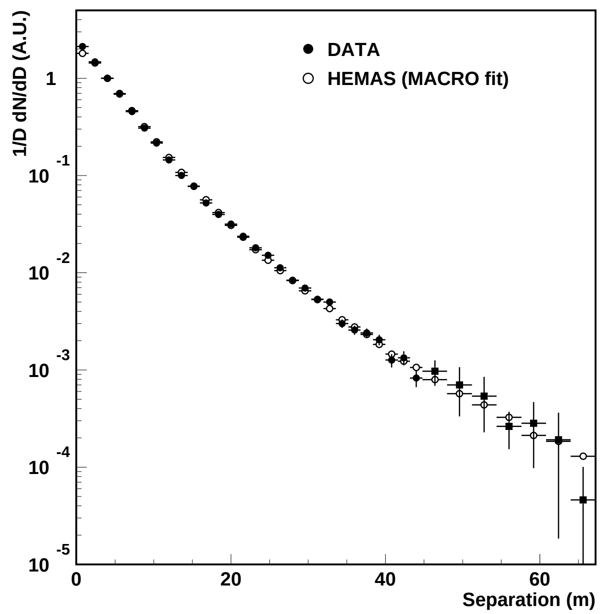

Figure 1. Experimental decoherence distribution (corrected for the detector effects) compared with the predictions of the HEMAS Monte Carlo (MACRO-fit primary composition model)

4.2. Cluster Analysis

The search for substructures inside muon bundles is able to provide additional information with respect to traditional methods [19]. In some events muon bundles appear to be splitted into "clusters" and we ask if this feature is the result of simple statistical fluctuations in the muon lateral distribution or if there is some dynamical correlation connected with the development

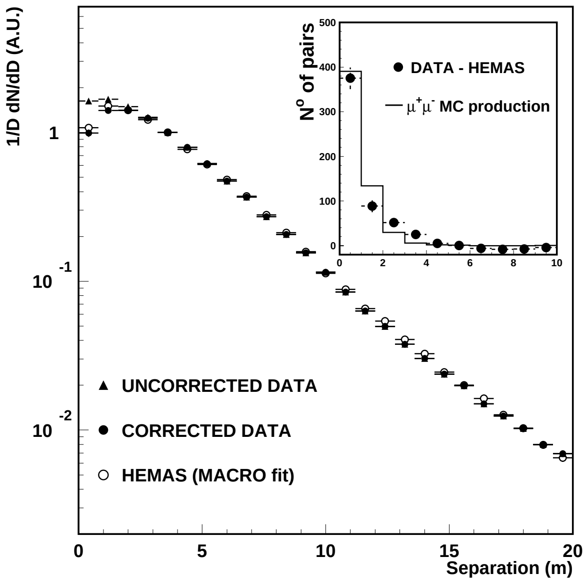

Figure 2. Zoom of the low distance region of the decoherence function before and after the inclusion of muon pair production process, and comparison with the Monte Carlo. In the inset it is shown the difference of the distributions before and after the correction, compared with the expectations of the Monte Carlo.

of the shower in the atmosphere. From an experimental point of view, we select muon bundles with at least 8 muons underground ($N_\mu \geq 8$) corresponding to CR primary energies $E_{primary} \gtrsim$ 1000 TeV. The search for muon clusters is performed by means of an iterative cluster finding algorithm, which groups the muons depending on the choice of a free parameter called χ_{cut} (for the definition of this parameter see Ref. [19]).

In Ref. [19] has been pointed out that this method is sensitive both on the primary composition model and on the hadronic composition model. The comparison was made between two extreme composition model (the “heavy” and “light” composition models [20]) and between two very different hadronic interaction model (HEMAS and NIM85). Most of the effect can be explained as the result of fluctuations of the muon *density* inside the bundles. Considering that the density (namely the average number of muons per unity of area) depends both on primary mass number and on the modelling of meson transverse momentum, we can expect that the cluster effect is sensitive to the composition model and to the hadronic interaction model at the same time. On the other hand, if we consider the interaction models quoted in previous sections, the sensitivity of the cluster effect on the interaction model becomes weaker. This is shown in Fig.3, where is reported the cluster rates as a function of the parameter χ_{cut} for different interaction models and for a fixed primary composition model (the model derived from the fit of the MACRO multiplicity

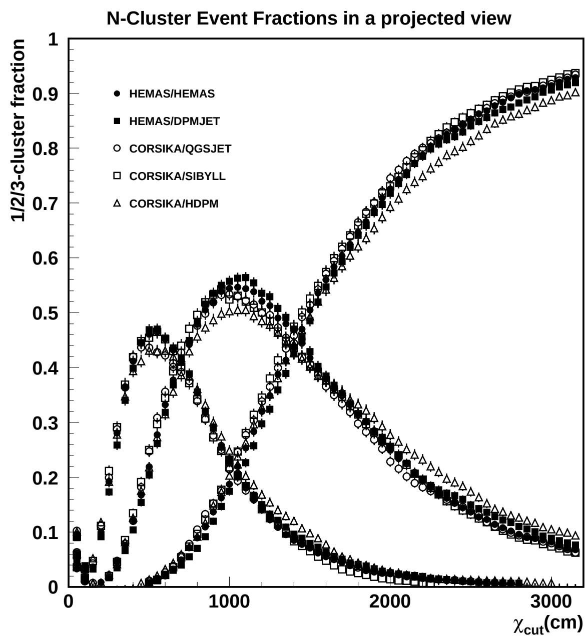

Figure 3. Fraction of events with 1,2 and 3 clusters in muon bundles for different hadronic interaction models. The detector effects have been considered and all the simulations have been obtained with the MACRO-fit composition model.

distribution [2]). In this case we are forced to enhance the sensitivity applying some selection criteria which correlate the underground substructures with the hadronic interaction features in the atmosphere.

Apart from statistical fluctuations, a Monte Carlo study has revealed other two mechanisms responsible for the cluster effect:

• muons belonging to the same cluster have a larger probability to have a common parent meson in the steps of shower tree generation;

• muons belonging to the same cluster are the decay products of mesons highly correlated in the phase space of the very first hadronic interactions in the atmosphere. We considered only events reconstructed as two-cluster events by the algorithm with a fixed χ_{cut} and we studied the kinematical variables pseudorapidity η and azimuthal angle ϕ of the parent mesons in the first interaction of the shower. The typical topology of these selected events is a muon rich cluster close to the shower axis, generally the remnant of the shower development after many steps, and a far cluster with few muons directly generated in the very first hadronic interactions. Fig.4 shows the distributions of the relative distance in the $\eta - \phi$ space of pairs of muon parent mesons originated in the first interactions: the topological selection of muons belonging to the same or to different clusters reflects in a strong selection of different phase space regions of hadronic interactions.

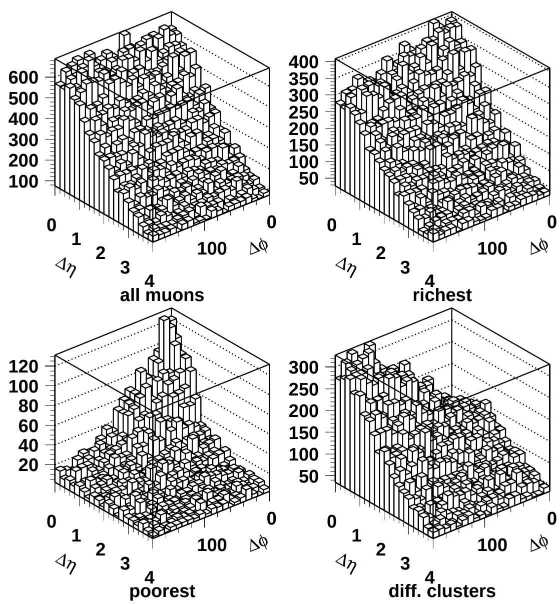

Figure 4. 2-dimensional distributions of the distance of first interaction mesons in the $\eta-\phi$ space. It is shown the case of no selection, of the selection of muons belonging to the same cluster (poorest or richest) or to different clusters.

A quantitative computation of the relative contributions of these effects is at presently under study.

5. CONCLUSIONS

The MACRO experiment has collected a large amount of muon data in the last decade. The analyses performed with these data allowed to draw conclusions about several items of muon physics. The dimension and granularity of the detector allowed the detection of multiplicity up to ~ 40, under more than 3000 hg/cm^2 of rock overburden. The study of the multiplicity distribution has been used to extract informations on the primary cosmic ray composition.

The modelling of the transverse component of the interaction models at TeV energies, connected with the lateral distribution of cosmic ray shower, is one of the main source of uncertainties in the simulation codes. The analysis of the decoherence function has shown the reliability of the HEMAS Monte Carlo, used in most of the MACRO analyses.

The study of second order effects, like the search for jet substructures inside muon bundles, is a useful tool to add new informations with respect to conventional analyses. The physical interpretation of the results has shown the dynamical origin of the effect, connected with the development of the shower in the atmosphere.

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